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DIASTROPHISM AND THE FORMATIVE PROCESSES

X. THE ORDER OF MAGNITUDE OF THE SHRINKAGE OF THE EARTH DEDUCED FROM MARS, VENUS, AND THE MOON

T. C. CHAMBERLIN
The University of Chicago

PRELIMINARY CONSIDERATIONS

During the last century it was the prevalent view that the earth was once a white-hot liquid globe. It was a logical inference from this view that the subsequent shrinkage of the earth arose chiefly from a loss of heat and from effects incidental thereto. On critical inquiry, however, it was found that the contraction assignable to lowering of temperature was disappointingly small. On the other hand, it was found as field inquiry was extended that the sum total of surface shortening implied by foldings, crumplings, overthrusts, and similar evidence was distinctly large. As a result of these divergent disclosures, students of diastrophism came to feel not a little hesitation in following out fully and freely to their logical limits the trend of interpretations suggested by field evidence whenever very great shrinkage was foreshadowed. The restraint thus felt was much like that suffered during the same period from supposed limitation of geologic time, a restraint now happily removed.

A radically new aspect, however, was given to the whole problem of earth shrinkage when, near the opening of this century, it was

discovered that certain of the heaviest known atoms were spontaneously giving out heat as an incident of their own disintegration. It was found that if radioactive substances pervade the whole body of the earth as richly as they do the accessible portions, the heat generated by them would be much greater than the amount the earth is now discharging at its surface. The certainty that the earth had been cooling at once disappeared; it seemed quite as likely that the temperature of the earth was rising as falling and, so far as heat is concerned, the volume of earth quite as likely swelling as shrinking. This cut at the very roots of the former tenet that shrinkage was chiefly due to the lowering of the temperature. The possible potentialities of the new source of heat were not only embarrassing in themselves, but they made the great heat hypothetically inherited from the white-hot earth a superadded burden of embarrassment instead of the facile explanation of shrinkage and deformation it had once been supposed to be.

Nor was this all: It was obviously necessary to devise some special hypothesis to obviate the surplus of heat the radioactive substances would give if they had a uniform distribution throughout the interior of the earth. Since no pressure or other physical condition is known to reduce appreciably the thermal output of radioactivity, a restriction of the radioactive substances themselves to a shallow surface shell seemed the only hypothesis available. But here the tenet of a molten globe arose as a new form of embarrassment. The radioactive substances are exceptionally heavy, and in a liquid mass they should naturally concentrate toward the center, not toward the surface. Convection, of course, if it were sufficiently active, might be supposed to prevent much concentration toward the center, but convection carries down as well as up and tends to give a more or less uniform distribution—just the distribution the hypothesis is seeking to avoid.

Nor is this the limit of the embarrassments attending the old view. A molten state implies that the larger part of the potential resources of shrinkage were exhausted before the formation of a crust made a record of shrinkage possible, at least so far as shrinkage depends on arrangements and combinations of material. A molten state offers nearly ideal conditions for the physical adjustment of

all constituent elements and for such chemical combinations as are possible, except in so far as the heat itself stands in the way. With such extraordinary facilities for selective adaptation as were hypothetically offered by the passage of the earth substance from the assigned gaseous to the liquid state and thence at length on to the solidifying state, a large part of all possible adaptation to the demands of pressure—save those restrained by heat—should have taken place before the record of diastrophism began. About all shrinkage left to be registered would be the meager amount that might spring from cooling.

Thus in several vital ways the inherited theory of a molten earth came to be a source of embarrassment to investigators who were struggling with the specific demands made by the field evidences of actual diastrophism.

THE WORKING FITNESS OF THE ALTERNATIVE VIEW

However, the case was desperate only from the traditional point of view. These embarrassments may be avoided if the gaseo-molten hypothesis is replaced by some form of the view that the earth was built up by the accession of solid particles brought to the earth in succession at intervals. In an earth so built the aggregate should have retained very nearly its maximum resources of combination, adjustment, and compression, while at the same time it was contributing only a small measure of heat to embarrass the threatened oversupply from radioactivity.

Furthermore, this view affords an easy and natural explanation of the concentration of radioactive substances at the surface. Under this view the radioactive particles came to the earth at random with the rest of its material. Their spontaneous heat was readily radiated away until they became buried to depths that prevented its ready escape. They then tended to become centers of local liquefaction. In so far as this was realized they became enveloped in their own mobile products and were thus carried by the extrusive agencies up to the cold zone or the surface. The liquid blebs thus generated, carrying their self-heaters with them, were well equipped for making exchanges with the eutectic substances encountered on their way out and for concentrating these

in the ascending thread of lava, leaving behind the less eutectic substances. They were thus well fitted to fulfil three functions: (1) to flux their way upward, (2) to separate the more fusible material from the less fusible, and (3) to carry the former out to the cold zone or the surface, taking along the chief source of heat and the heat already generated. By thus draining away selectively the more fusible elements in the mixed material and raising the mean resistance of the rest to fusion, they help to maintain the solidity of the main mass. It is obvious that adjacent threads of hot self-heating lava must render one another assistance in mutually uniting and massing their forces for fusing their way outward. After such tracts have been drained of their more fusible substances and the conduits closed, new paths in ground less depleted of its eutectic material would naturally be chosen and thus the selective work should at length cover the whole field and raise its mean fusion-point, while the self-heating radioactive particles were more completely removed.

At all stages of this selective process it is held that the differential stresses of the earth body lent effective aid in extruding the liquid matter. The great pervasive stresses of the earth, static and dynamic alike, are intensest in the deep interior and graduate outwardly. The differential components of these are well suited to squeeze toward the surface the liquefying portions of the interior matter about as fast as these accumulate in sufficient quantities to respond readily to such stresses, while the liquids themselves readily yield to the rise by reason of their heated state and the gases they gather to themselves. To this doubly facilitated extrusion of liquid matter carrying its special thermal source with it is assigned the function of clearing the depths of their original radioactive substances and of their heat products, with the incidental effect of perpetuating the solid state of the earth as a whole.

If the simile may be pardoned, the liquid threads may be likened to the sweat pores of an organic body, regulating its temperature by a natural perspiratory system. The pools of lava that at times accumulate at the surface function as the sweat drops of the earth body. They seem large, to be sure, in terms of ordinary

measure, but they are really quite minute when compared with the 260,000,000,000 cubic miles of the earth mass.

It will be noted that this view is a reversal of the old interpretation. Instead of being a residual effect of former excessive heat, extrusive igneous action is initiated automatically within the body and forms a regulative system through which the solidity of the globe is maintained. The extrusive action is at the same time merely a minor feature in a general genetic process that has conserved the potential resources of shrinkage and rendered them available at such successive stages in the history of the planet's evolution as developed the conditions necessary to call them into action.

But, notwithstanding the ampler possibilities of shrinkage which this newer view places at the command of students of diastrophism, the pall of restraint has not as yet been wholly lifted. Thus far there has been no well-grounded estimate of the total earth shrinkage that has actually taken place. Even a theoretical estimate of the shrinkage available for interpretative assignment is still lacking. Workers in this field are thus still more or less under the shadow of restraint. Research will certainly proceed with more equipoise if workers can feel wholly untrammeled by supposed limitations in following to their logical conclusions any leadings of evidence they may encounter, even though its demands may be greater than general considerations have thus far seemed to warrant.

THE SPECIFIC FIELDS THAT YIELD DIASTROPHIC EVIDENCE

A glance at the field evidences of diastrophism will further prepare the way for a study of the probabilities of the case. Diastrophism is displayed in three great fields. These are closely related, to be sure, but yet sufficiently different to require individual recognition.

I. The first embraces the deformations of the distinctly stratified terranes, chiefly those of the Paleozoic and later ages. These are relatively accessible, and the constituent formations usually so far retain their individuality as to be susceptible of being satisfactorily traced throughout the whole tract involved in the deformation under study.

II. The second embraces the complicated distortions and the metamorphosed phases of the Proterozoic and Archean complexes. Usually these are only partially accessible, and the profound changes they have undergone present formidable difficulties in addition.

III. The third includes the deeper and more massive deformations of the earth body. These can be regarded as accessible only in a logical sense by means of indirect evidences or remote intimations, or by a priori considerations.

I. In the more surficial of these three fields estimates of crustal shortening have been made from time to time in the past, but in the main these have been confined to linear shortening; they have not included the depths involved in the shortening. This is necessary for computing their total quantitative values. Nor has there usually been any determination of the under-configuration of the distorted masses. This carries a very important part of the specific significance which the diastrophism embodies. A notable beginning has been made in adding these two neglected factors and increasing at the same time the reliability of the estimate of the linear factor.[1] But the labor involved in these more adequate determinations is so large that much time must pass before a sufficient number of such determinations can be made available for a total estimate of the shrinkage involved in even the limited field to which the method is adapted.

II. In the Proterozoic-Archean field there is little ground to hope for any general application of these superior methods, partly because of the large measure of concealment of the terranes and partly because of the excessive intricacy of the structure and the frequent changes in petrologic nature which render sharp identifications of the borders of the several members of the terrane throughout the whole folded tract impracticable. The difficulties of this field are formidable in the extreme. No one, so far as I know, has thus far had the temerity to offer an estimate of the amount of shortening implied by the intricate crumpling of these

[1] Rollin T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. of Geol.*, XVIII (1910), pp. 228-51; "The Building of the Colorado Rockies," *ibid.*, XXVII (1919), pp. 145-64, 225-51.

old formations on any great circle of the earth. That it was large, however, goes without the saying.

But, taken at their best, the deformations in these two fields are merely surficial. Such foldings as are accessible are mere wrinklings of the skin of the earth body, mere lineaments of the face of the earth. They have about the same relation to the effective framework of the earth body as the shriveled integument of an old man has to the bony skeleton that chiefly gives form to his figure.

III. The deeper deformations of the earth have been little more than a field for the imagination thus far. And yet they have given rise to indirect and implied evidences. There are the protrusions of the continents, the sags of the sub-oceanic basins, and the general configurations of the globe. There are tidal, seismic, magnetic, and other dynamic lines of approach. Great light has been thrown on the problems of the interior by the brilliant determination of the value and nature of the body tide and the elastic rigidity of the earth by Michelson and Gale on the experimental side,[1] and Moulton on the mathematical side.[2] The seismic evidences gathered by many observers indicate that the elasticity of the earth increases downward faster than the density for at least a depth that involves much more than half the volume of the earth. These trenchant determinations bear vitally on the interpretation of the internal deformation of the earth.

The lines of approach now available for an interpretation of the master-features of the earth's surface promise at least some insight of value into the earth's fundamental diastrophism. I have ventured to interpret these master-features as simply the adult products of a segmentation that sprang from primitive shrinkage stimulated and shaped by oscillating rotation and tidal strains.[3] Under this view there are cogent reasons for assuming that the original segments were more or less unequal and asymmetric, and

[1] A. A. Michelson and H. G. Gale, "The Rigidity of the Earth," *Jour. of Geol.*, I (1919), pp. 585–601.

[2] F. R. Moulton, "Theory of Tides in Pipes on a Rigid Earth," *Astrophys. Jour.*, L (1919), pp. 346–55.

[3] *The Origin of the Earth* (1916), pp. 200–224.

that the large inequalities and asymmetries now observed are largely due to later shiftings, distortions, and outgrowths of the primitive elements. These then are the special subjects of study in the third field of diastrophism.

THE PARTICULAR OCCASION FOR THIS INQUIRY

Now in a recent study of what could plausibly be assigned to original irregularity in segmentation and what then remained to be assigned to subsequent movements and unequal growths, I was led to see, or to think I saw, evidence of a system of shiftings and of unequal growths which marshaled themselves in a singularly rational way as though they were due to systematic causes of a general nature. The particular adjustments appeared to be such as were directly implied by the configurations which the great features now bear. By reasoning back from the present configurations to the assigned primitive configurations, rather specific amounts of shiftings and deformations, abetted by unequal outgrowths, seemed to be indicated. The amounts of these shiftings were distinctly larger than the movements commonly assigned to diastrophisms in the surficial fields. Because of this largeness the question, How much shrinkage can reasonably be assigned the earth during its whole history? came up in a new and specific form, and with especial piquancy by reason of unexpectedly exacting demands.

COMPARISON BETWEEN THE EARTH AND ITS NEIGHBORS

In casting about for some independent means of estimating such reasonable possibilities or even probabilities of shrinkage as there might be under the later view of the constitution of the earth, a comparison of our planet with its near neighbors, the moon, Venus, and Mars, suggested itself, as also a comparison with an ideal earth built of material of the average meteoritic type.

The earth, Venus, Mars, and the moon form a little group of closely related bodies revolving in the inner part of the sphere of control of the sun under very similar dynamic conditions. We naturally think of them as widely deployed, but, taken all together, the little group spans less than 3 per cent of the radial reach of

the solar system and probably not more than a thousandth part of the radius of the sun's sphere of control. This last is the more significant standard, for the sun's sphere of control is the dynamic field within which the planets had their origin and have ever since had their being. It is therefore a reasonable inference that the members of the little group shared much the same evolutionary conditions, were formed in much the same way, and of much the same material. But even if there was some gradation in the nature of the material due to position in the system—which we will consider later—its effects are measurably equated in the comparisons, because Mars lies outside the earth and Venus inside, while the moon, as a member of the earth system, presumably partook of the common material from which both earth and moon were derived, though perhaps not in precisely the same way. At any rate, though some differences of original material must be presumed to have entered into the formation of these four bodies, such differences could scarcely have been at all radical. Besides, it will be seen later to be possible to deduce the more important differences which affected the selection of material in the formation of these bodies. This will be considered in an article following this one, as it goes too far afield to be introduced here.

All members of this little group of bodies are small compared with the four giant planets outside them, and yet they are large relative to the majority of satellites and planetoids. They form an intermediate group, and deductions respecting them may be checked by the extremes on either hand. Among themselves they form a graded series well suited to our purpose. The moon is distinctly small and has no appreciable atmosphere or hydrosphere; it may be taken to represent such bodies as are formed of molecules heavy enough and sluggish enough to be controlled by a limited attractive force, a force too feeble to hold the lighter and swifter order of molecules. Mars represents a stage of growth at which sufficient gravitative power has been reached to maintain a limited atmosphere and apparently the beginnings of a hydrosphere. Venus represents a much more advanced stage at which the gravitative power is sufficient to hold a very notable atmosphere and probably a rather massive hydrosphere. The earth, as we

well know, represents a stage at which a notable atmosphere and a distinctly massive hydrosphere have been acquired and held. The four bodies thus represent those stages of evolution which are most significant in such a study as this. They are all notably dense compared with the great planets that lie outside them and with the sun at the center of the system. The moon, Mars, and Venus will be treated as representing a typical series of stages of evolution connecting the small atmosphereless type with the largest known cold planet enveloped with a deep water-sphere and gas-sphere, the earth. No special study will be given to the large hot bodies of low density that form the great outer group.[1]

STATISTICAL DATA

Some of the more essential statistics on which the study will be based are gathered into Table I.

TABLE I*

Planet	Mean Diameter in Miles	Mass Earth = 1	Density Water = 1	Surface Gravity g = 1
Moon	2160 (3476 kms.)	0.0122	3.34	0.16
Mars	4339 (6983 kms.)	0.1065	3.58	0.36
Venus	7701 (12394 kms.)	0.807 (?)	4.85 (?)	0.85 (?)
Earth	7918 (12743 kms.)	1.000	5.53	1.00

* These statistics are taken from Moulton's *Introduction to Astronomy*, Revised Edition, 1916. Venus has no satellite and its mass and density can only be determined by indirect means which are not very accurate, and hence the figures for these are marked with an interrogation point, but they are probably close enough for our purpose. The figure 5.53 for the density of the earth is conservative; figures as high as 5.56 and 5.57 have been used. These higher figures would give greater shrinkage. The dimensional data are given in miles and in kilometers, but the computations are carried out in miles, because, being the larger unit, it is the more convenient. An even larger unit is desirable for most earth studies and so the standard degree of a great circle of the earth is added in circumferential measurements. Degrees are convenient units in working with globes.

THE METHOD OF THE INQUIRY

As a step preparatory to the proposed comparison there were built up from the moon, Mars, and Venus, each in turn, by using material of its own mean density, parity-earths whose masses were equal in each case to that of the actual earth. A similar parity-earth was built up of mean meteoritic material. The radii and volumes of these parity-earths were then computed and taken as

[1] Cf. W. D. MacMillan, "On Stellar Evolution," *Astrophys. Jour.*, Vol. XLVIII, No. 1 (July, 1918), pp. 40–41.

the basis of shrinkage. The parity-earths were supposed to shrink until their mean densities were identical with that of the present earth. The amount of this shrinkage is recorded in Table II in terms (1) of the earth's radius in miles, (2) of the earth's circumference in miles, and (3) of the earth's circumference in degrees, each of these being more convenient than the other in certain specific uses.

In building up the meteorite earth Farrington's mean specific gravity of meteorites seen to fall was taken as the basis of computation.[1] While the inclusion of only those meteorites that have been seen to fall may not be strictly representative, it is Farrington's view that this limitation gives the best definite figure that is available. If the meteorites found but not seen to fall were included, the specific gravity would quite certainly be too high, because metallic meteorites are more likely to attract attention on account of their unusual heaviness and the whitish color of the metal, and because they are less liable to disintegration than the stony meteorites. Nevertheless, if all meteorites that have reached the ground in observable masses were averaged, the mean specific gravity would probably be greater than the figure given. On the other hand, the surfaces of iron meteorites are notably pitted, due probably to the exfoliation of the stony parts, as these are less tenacious than the metallic parts. A naked body sweeping about the sun and likely to be in rotation is quite sure to be subjected to those rapid changes of temperature which promote exfoliation. The gravitative power of a meteorite is very small and hence these exfoliated chips would be likely to be thrown off into separate paths and thereafter play the part of individual meteorites. It is thus probable that the vast multitude of small meteorites that are burned to dust in the upper atmosphere are much more largely stony than metallic. This consideration probably offsets any weight that ought to be given to the preponderance of metal among the meteorites found some time after their fall. At any rate the mean given by Farrington is the best available and is doubtless near enough the true mean to give the right order of magnitude to the results deduced from it.

[1] O. C. Farrington, *Jour. of Geol.*, V (1897), pp. 126–30.

While meteorites in the main seem to belong to the solar system, they appear to be samples from many sources. for they are extremely numerous and come to the earth from various directions and at very different velocities. It is therefore thought that they fairly represent the nature of any kind of scattered interplanetary matter of the solid type that might once have been available for the formation of small planets and satellites. This view does not rest so much upon their present status as upon the dynamics of the case, for the self-aggregation of small masses implies feeble gravitative control, and under the conditions of such feeble control only the heavier, sluggish molecules can be gathered and held. For this reason meteoritic material is taken to represent the densest type of scattered solid particles and small masses, whether planetesimal, satellitesimal, meteoritic, or otherwise, available now or in the past, for the growth of satellites and planets. This of course does not exclude the availability of lighter material, even gaseous material, to planets massive enough to hold such material, nor does it exclude occluded or combined gases from even the smallest bodies.

In building up these parity-earths, the series starts with the moon, the lowest in mean density, rises thence through Mars and the representative meteorite, to Venus, next to the earth in mean density, and ends with our planet. This arrangement should suggest at once that as the last two are the most massive bodies and hence have the greatest power of holding light molecules, they probably have the largest proportions of inherently light matter in their composition.

THE NUMERICAL RESULTS

The leading numerical results of the computations are gathered into Table II.

Let us hasten to admonish ourselves that these results are as yet uncriticized. Before the inquiry may properly rest these results must be scrutinized in the light of the dynamical conditions under which the four bodies were formed, for these conditions were such as to determine the inherent heaviness or the inherent lightness of the matter that formed them. This critical phase of the study will take us rather far afield and must therefore be deferred to a later article. I feel warranted, however, in saying that this further study will indicate, as does the hint given above, that the more massive

bodies in all probability contain the larger proportion of light atoms and molecules and that the shrinkage figures of Table II will need to be somewhat increased to satisfy the natural intimations of the laws of planetary organization. For the moment, however, let us regard these prospective increments merely as a measure of assurance that we will be forming first impressions on conservative grounds if we tentatively review the results as they stand. If this review shall raise any questions as to the validity of the results deduced these questions will serve to give piquancy to the deferred discussion.

TABLE II*

Basis of Parity-Earth	Density Water = 1	Present Radius	Present Volume Cubic Miles	Parity-Volume Cubic Miles	Parity-Radius Miles	Shortening of Parity-Radius Miles	Shortening of Parity-Circum. Miles	Shortening of Parity-Circum. Degrees
Moon........	3.34	1080	5,276,678,626	430,353,000,000	4684	725	4555	66
Mars........	3.58	2170	42,802,469,494	401,502,000,000	4577	618	3883	56
Meteorite.....	3.69	....	....	389,506,000,000	4531	572	3594	52
Venus........	4.85	3851	239,226,992,649	296,367,000,000	4136	177	1112	16
Earth........	5.53	3959	259,923,849,377	....	....	...	....	..

* The parity-earths may be derived either from the relative densities or the relative masses. The results, however, are not strictly identical in all cases, doubtless because the figures adopted are the weighted means of different methods of determining the masses and densities and these thus lose strict consistency with one another. The differences are not enough seriously to affect the order of magnitude of the shrinkage results.

PROVISIONAL DISCUSSION OF THE RESULTS

On first thought it may seem that the observed densities of the four bodies compared can be easily accounted for by assigning such specific gravities as are requisite to the material that entered into their formation. Thus the computed amounts of shrinkage may seem to be avoided. If it is legitimate to make purely arbitrary assignments in neglect of the laws of cosmic organization under such hypotheses of genesis as are tenable, no doubt this might be done. But in a naturalistic inquiry that tries to be thoroughly loyal to cosmic laws, so far as the inquirer knows them or can find them out, arbitrary assignments have little or no place. We are here dealing with highly composite results, the products of natural processes of organization. Each of the four bodies is believed to have been formed by a multitude of accessions brought together by forces of like types, acting under similar conditions and surrounded

by similar dynamic environment. It does not seem naturalistically probable that arbitrary variations of sufficient moment to affect the average order of results could have entered into these combinations so closely analogous in general nature. It is well recognized that under the law of probabilities a multitude of random contributions, uniting under common conditions, give closely concurrent averages even though the individual contributions may be highly variant. It will be seen from the discussion in the succeeding article that a very definite law probably presided over the proportion of the inherently heavy to the inherently light material which entered into the formation of the four bodies compared. Taking then their systematic organization for granted for the time being, the following tentative points are to be noted:

I. The total shrinkage of the earth implied by the comparisons is very large. A circumferential shrinkage of 4,555 miles in a putative growth from a moon stage by the addition of moon-stuff is certainly large. A similar shrinkage of 3,883 miles in a growth from a Mars stage by the addition of Mars-matter is quite as notable; and a shrinkage of 1,112 miles in a growth from a Venus stage—a stage in which 80 per cent of growth has already been attained, while the material added has the high density of Venus—is even more remarkable. These large shrinkages are ample to meet all the demands that gave rise to the inquiry and leave a good working margin beside.

II. Since the four bodies were treated as spheres, the computed shrinkages apply to all great circles, meridional, oblique, or equatorial, equally. The special deformations that may be assignable to changes in the rate of rotation are not here included. There was probably always some equatorial bulging and polar flattening, but the geological evidence does not seem to imply that deformations of this class were essentially greater during the early ages than they have been during the later ages.[1] The large shortening in meridional circles given by the computations satisfies the requirements of the Archean crumplings and related phenomena of the high latitudes, which seem to be essentially as great as those of low latitudes.[2]

[1] "The Tidal and Other Problems," *Publication No. 107*, Carnegie Institution of Washington (1909), p. 51.

[2] *Loc. cit.*

THE STAGE OF MAXIMUM SHRINKAGE

If the four bodies under comparison are to be regarded as representing stages of growth, it is a matter of much added interest to deduce from the comparison the stage of growth at which the greatest shrinkage took place. If the bodies were entirely compact at the outset, as they would be if fluid, or pliantly viscous, shrinkage from gravitative pressure might be expected to decline with every stage of compression reached, because resistance to compression usually increases rapidly as compression proceeds; but if the material of growth were minutely fragmental at the outset and the particles rigid and elastic, other factors of importance would come in. At first the porosity would be great. Until the porosity was exhausted the shrinkage would depend largely on the rigidity and the elastic qualities of the constituent particles. Later, the possibilities of chemical, crystalline, and physical readjustments in the interest of density would come into service. Another factor is the presence or absence of effective wash, solution, and redeposition. These are dependent on the presence or absence of an effective hydrosphere. The moon has neither appreciable atmosphere nor hydrosphere and if originally built up of minute rigid particles it would retain a deep porous zone of relatively low specific gravity. This would notably affect its mean density. Besides, there is evidence of much explosive eruption and the pyroclastic products arising from this would, in the absence of wash, solution, and redeposition, remain highly porous. The *Mare* once regarded as seas and later as lava plains may perhaps really be tracts of volcanic ash. Lines of projected débris crisscrossing *Mare Imbrium* are well shown in a recent photograph by the 100-inch reflector of Mount Wilson. Mars is on the ragged edge of doubt; it may perhaps have enough water on its surface to wash fine material from the exterior into the interior and to dissolve more or less of the surface material and deposit it in the pores below, or, on the other hand, the water may be so scant as to have little effect in cementing and solidifying the outer zone of the planet. But in the case of Venus, inwash and cementation are probably efficient, while they are known to be on the earth. All these factors seem to have played important parts in the results.

An inspection of the mean densities themselves gives some hint of the general nature of the compression: 3.34 for the moon, 3.58 for Mars, 3.69 for meteorites, 4.85 for Venus, and 5.53 for the earth. It is notable that the mean density of meteorites falls between the two bodies suspected of deep porosity and the two bodies in which wash, solution, and cementation are effective.

The results given in Table II bear an analogous import: 725 miles radial shrinkage for the lunar parity-earth; 618 miles for the Martian parity-earth; 572 miles for the meteorite parity-earth; and 177 miles for the Venus parity-earth. However, these shrinkages represent quite different ranges of growth; to be strictly comparable they must be reduced to a common basis. A convenient unit is an increase equal to 1 per cent of the mass of the earth. This is equal to the weight of about 14 billion cubic miles of water. Reducing the several shrinkages to this unit of mass increase, they become: for the mean rate of shrinkage between the moon stage and the mature earth, 7.44 radial miles per unit increase of mass; between the Mars stage and the mature earth, 6.90 radial miles per unit; and between the Venus stage and the mature earth, 9.17 miles per unit. This brings to attention the very suggestive fact that the rate of shrinkage per unit of mass increase *is greatest in the last stage*. Next to this, it is greatest in the growth from the stage represented by the moon, the body suspected of being the most porous, and the least affected by wash, solution, and cementation. The first seems to imply that massiveness is the dominant influence. Next to this porosity seems to be influential.

These inferences will appear to be still more strongly suggested if we reduce all the four natural bodies to parity-bodies, using mean meteoritic material as the basis. The results appear in Table III.

The third column shows that if the moon had been built up to its present mass with material of the mean density of meteorites, its radius would fall short of what it actually is by 35 miles; if Mars had been built up in a similar way its radius would be 22 miles short, while the radius of Venus built in the same way would be 367 miles greater than it actually is, and the radius of the earth under like conditions 572 miles greater than it is. If all these bodies were actually built up of mean meteoritic material the figures

would seem to mean that the porosity of the moon is represented by 35 miles in terms of radius, over and above such compression as its center has suffered. This may be taken tentatively as representing the deep porosity of the moon. Similarly, the porosity of Mars would be represented by 22 miles in excess of its central compression. On the other hand, the actual compression of Venus seems to be represented by 367 miles, while the corresponding figure for the earth is 572 miles.

TABLE III

COMPARISON OF METEORITE-PARITY WITH ACTUAL BODIES

Body	Radius Actual Body Miles	Radius Parity-Body Miles	Radii Differences Miles	Mass Units 1 Per Cent Earth Mass	Shrinkage Between Parity-Body and Actual Body per Unit=1 Per Cent Earth Mass Miles
Moon........	1080	1045	− 35	1.22	−28.7
Mars........	2170	2148	− 22	10.65	− 2.0
Venus........	3851	4218	+367	80.70(?)	+ 4.5
Earth........	3959	4531	+572	100.00	+ 5.7

In the fifth column the degrees of compression are reduced to a common unit-mass. This brings out the essence of the matter in a striking way. It appears that the moon, built up as it actually was, failed to compress itself to the meteorite standard by 28.7 miles per unit of mass-growth, and Mars by 2.0 miles per unit, while Venus compressed itself beyond the meteorite standard to the extent of 4.5 miles per unit of mass-growth, and the earth by 5.7 miles per unit. This seems to put the first two bodies in one category and the last two in quite another category, while it greatly emphasizes the progressive nature of the compression from the least to the greatest, even per unit-mass of increase.

Let us, however, hold all these tentative results in abeyance until we have more critically considered the probabilities in respect to the inherent nature of the material that entered into the constitution of these four bodies. Meanwhile this preliminary inspection may serve to give point to the study of the genetic conditions that affected these results. This study will be the theme of the succeeding article.